Title	Emulating a large-scale quantum Internet
Sub Title	
Author	Van Meter, Rodney(Kusumoto, Hiroyuki) 楠本, 博之
Publisher	
Publication year	2016
Jtitle	科学研究費補助金研究成果報告書 (2015.)
JaLC DOI	
Abstract	量子インターネットの開発と実現のため, 最重要となる基幹技術が異なったネットワーク同士の接続方法を開発し, シミュレーションによって挙動を確認した。必要となる全ての関連技術をデザインし, 再帰的経路セットアップアルゴリズム及び分散量子状態のソフトウェアによる管理手法を開発した。量子インターネット全体のシミュレータは現在開発中となる。また, 「量子スニーカーネット」の概念を開発し, シミュレーションを行った。これにより例えばコンテナ船で量子ビットを移送し海を越える量子もつれが作成可能である。さらに, 混合状態を用いた量子ネットワークコーディングを開発し, シミュレーションにより使用可能な状況を確認した。 We have solved key problems in the development and deployment of a true quantum Internet. Most important among these, we have designed and simulated a mechanism for building entanglement end-to-end along a path through the quantum Internet, crossing boundaries between different types of quantum networks. All key mechanisms have been designed, most importantly the recursive path setup algorithm and software management of distributed quantum states. The complete Internet simulation remains in development. We developed and simulated a "quantum sneakernet" mechanism, for building entanglement using entangled quantum states moved via container ship. We simulated quantum network coding using mixed quantum states as a "middleware" means of optimizing use of a Quantum Internet, and established that penalties on end-to-end fidelity are acceptable.
Notes	研究種目 : 基盤研究(B)(一般) 研究期間 : 2013～2015 課題番号 : 25280034 研究分野 : 量子ネットワーク
Genre	Research Paper
URL	https://koara.lib.keio.ac.jp/xoonips/modules/xoonips/detail.php?koara_id=KAKEN_25280034seika

様　式　Ｃ－１９、Ｆ－１９、Ｚ－１９　（共通）

科学研究費助成事業　　研究成果報告書

平成 ２８ 年　 ６ 月　 ９ 日現在

機関番号： ３２６１２
研究種目： 基盤研究(B)（一般）
研究期間： 2013～2015
課題番号： ２５２８００３４
研究課題名（和文） Emulating a Large-Scale Quantum Internet

研究課題名（英文） Emulating a Large-Scale Quantum Internet

研究代表者
Van・Meter　Rodney（VAN METER, Rodney）

慶應義塾大学・環境情報学部・准教授

研究者番号：９０４５８９７７

交付決定額（研究期間全体）：（直接経費）　12,800,000円

研究成果の概要（和文）：量子インターネットの開発と実現のため、最重要となる基幹技術が異なったネットワーク同士の接続方法を開発し、シミュレーションによって挙動を確認した。必要となる全ての関連技術をデザインし、再帰的経路セットアップアルゴリズム及び分散量子状態のソフトウェアによる管理手法を開発した。量子インターネット全体のシミュレータは現在開発中となる。また、「量子スニーカーネット」の概念を開発し、シミュレーションを行った。これにより例えばコンテナ船で量子ビットを移送し海を越える量子もつれが作成可能である。さらに、混合状態を用いた量子ネットワークコーディングを開発し、シミュレーションにより使用可能な状況を確認した。

研究成果の概要（英文）：We have solved key problems in the development and deployment of a true quantum Internet. Most important among these, we have designed and simulated a mechanism for building entanglement end-to-end along a path through the quantum Internet, crossing boundaries between different types of quantum networks. All key mechanisms have been designed, most importantly the recursive path setup algorithm and software management of distributed quantum states. The complete Internet simulation remains in development. We developed and simulated a "quantum sneakernet" mechanism, for building entanglement using entangled quantum states moved via container ship. We simulated quantum network coding using mixed quantum states as a "middleware" means of optimizing use of a Quantum Internet, and established that penalties on end-to-end fidelity are acceptable.

研究分野： 量子ネットワーク

キーワード： 量子インターネット　量子リピーター

１．研究開始当初の背景

量子情報を離れているところに配るようになったら、いくつかの利用方法はあると知られている。鍵配送ではインターネット上の通信はもっと安全になる。分散量子状況を利用して、時計同期の時間精度は上がる。クライエント・サーバー型の分散量子計算は可能になる。

量子状況は非常にデリケートなので、配るのは難しい。この問題を解決するために、量子中継機（quantum repeater)の概念は開発された。量子中継機は三つの仕事がある：隣接ノードと量子もつれ(quantum entanglement)を作り、そのもつれを利用して直接繋がっていないノードに接続、そしてエラー管理。いくつかの中継機を設置して、量子ネットワークは可能になる。

量子ネットワークの構築に向けた研究は、ハードウェア設計やネットワーク挙動のシミュレーションなどが行われてきた。一方でその対象は直線経路や少数のノードからなるネットワーク解析に留まってきた。

複雑かつ大規模な量子ネットワーク同士が接続された量子インターネットの設計を行うには、通信経路の選択手法や輻輳する通信に対応した資源管理、管理者および通信手法の異なるネットワーク同士の相互接続方法など様々な問題を解決しなくてはならない。

２．研究の目的

現実的な物理的パラメーターやネットワーク構成をもつ量子もつれ中継ノード（量子リピータ）式ネットワークのエミュレータを開発し、新たなネットワークプロトコルを提案し、その実現可能性と性能を検証する。本エミュレータは、エミュレーションされるリンクを併用し、巨大量子インターネットを構築する。また、100 ノードを持つネットワークを 100 セット作り、合計 1 万ノード規模のものとする。また、この量子インターネットエミュレータには全世界からインターネットを通じてアクセスを可能とし、本研究で開発するプロトコルや技術を評価するのみならず、様々なテストベッドとして利用可能とする。これにより、本研究によって構築された量子インターネットエミュレータでは、将来、他の研究者が新たな技術を開発した際に、本システム上を用いて実装、評価を行うことが可能となる。

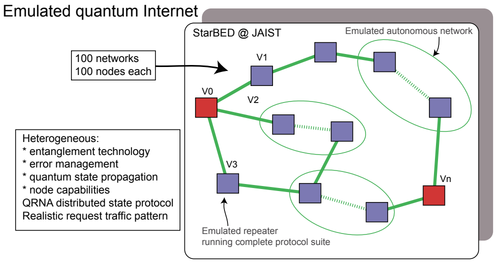


図 1 Emulated Quantum Internet

３．研究の方法

Our guiding principle in designing quantum networks and internetworks is to learn as much as possible from the research and development done over the last forty years for the classical Internet.

One goal of our research is to guide development of quantum repeater hardware, thus it is imperative that we be able to test ideas qualitatively without access to actual hardware. We performed simulations using a Python-based simulator that tracks Pauli frame errors with X, Y and Z error probabilities taken from the research literature.

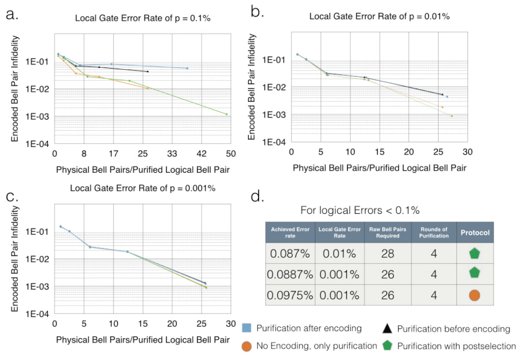
４．研究成果

1. We designed and simulated the key mechanism to achieve interoperability between different types of quantum repeater networks [1]. In our scheme, the creation of Bell pairs where each qubit is encoded in a different error correcting scheme is the primary service provided by Quantum Internet routers.

The three key types of quantum repeaters proposed to date are purify and swap [2]; CSS error correcting code based [3]; and surface code based [4]. *Purification* is a form of error detection useful for specific states, especially Bell pairs. Dur and Briegel showed how to combine purification with *entanglement swapping* to overcome the limitations on distance due to photon loss and error accumulation. This type of network will operate on physical qubits, but has the significant drawback that two-way communication is required over various distances, including end-to-end, reducing performance and increasing the demands on qubit memory lifetime and buffer capacities. To address this problem and better mesh with error-corrected quantum computers, Jiang *et al.* developed an error-corrected form of repeater that allows one-way communication while protecting quantum states with classically derived error correcting codes. Fowler *et al.* shortly thereafter proposed a mechanism using the quantum-unique error correction mechanism known as *surface code.* Additional types of networks have been proposed in recent years, but we expect that internetworking mechanisms developed to connect these three types of networks will be easily extended to newer types of networks; therefore, we have established design and simulation of a quantum Internet composed of networks of these three types as our primary goal.

We simulated pair-wise creation among those three network types of entangled, heterogeneously encoded quantum states useful for interconnecting disparate networks. Our algorithm begins with a physically entangled state (Bell pair), then expands each member qubit to a logically encoded state using the appropriate error correction.

In our simulations, we evaluated several mechanisms for improving the fidelity of the state, and find that purification after encoding with a strict post-selected mechanism performs the best. Alternatives evaluated include purification of the physical Bell pairs before the encoding operation, and purification after encoding without strict post-selection, both of which were found to result in logical states with higher residual error rates after using similar numbers of the base-level entangled qubit pairs.



For logical Errors < 0.1%

Achieved Error rate	Local Gate Error Rate	Raw Bell Pairs Required	Rounds of Purification	Protocol
0.087%	0.01%	28	4	⬟
0.0887%	0.001%	26	4	⬟
0.0975%	0.001%	26	4	●

図 2 Simulation results of interconnecting distance 3 surface code and Steane [[7,1,3]] code

図 2 shows simulation results for heterogeneous Bell pairs between a distance 3 surface code and the [[7,1,3]] Steane quantum error correcting code. With local gate error rates of 0.001%, the various mechanisms produce essentially indistinguishable results with the final infidelity determined by the infidelity of the initial Bell pairs. With higher gate error rates, however, we see the influence of our choice of encoding and purification mechanism, and at values around 0.1%, only post-encoding purification with strict post-selection produces logical Bell pairs of acceptable fidelity.

We expect that this mechanism will be the preferred means of creating entanglement between different types of networks on the Quantum Internet.

2. Concepts for distributed control of quantum states and the operation of repeaters and routers were developed. These concepts build upon and extend the Quantum Recursive Network Architecture (QRNA), to make it concrete [5].

In repeater networks, the component qubits of entangled quantum states are held in different locations, giving us distributed quantum states, controlled by classical software at separate nodes. Coordination of action among these nodes requires following these rules: (1) Alice and Bob (or all participants, for larger states) must agree on the state created (both the target pure state and the noise terms); (2) Alice and Bob must agree on the original creation time of the quantum state; (3) Alice and Bob must share an understanding of the time evolution of the density matrix (or at least fidelity), *with enough accuracy to guarantee consistent decisions*; and (4) Alice and Bob must run higher-level algorithms *at the same point in the sequence of operations* and *on the same list of states* [6].

We designed a rule-based mechanism for governing the actions of individual routers in a robust way that builds entanglement in a software-driven manner (described below).

We designed a path setup algorithm for establishing a connection that spans network boundaries, using a recursive mechanism that we expect to scale. Our algorithm operates in two phases: the path is first collected through an outbound probe sent by the *Initiator*, using selection of "next hop" nodes using mechanisms derived from classical network routing protocols [7], and collecting information about the path along the way. When the Responder receives the probe, it examines the path information, and establishes a set of *Rules* that are distributed node-by-node to the path elements on the return pass of the protocol.

3. Our simulations require a concrete model of node capabilities, so we established a technology-independent hardware architecture for quantum routers, building on the concepts of quantum multicomputers using optical interconnects, as shown in 図 3.

In addition to the hardware architecture, we have established a software architecture for each quantum router. The key element is the *Rule Engine*, which operates in soft real time to execute the set of rules for each connection that passes through the node. The Rule Engine is event driven, acting when classical messages are received from partner nodes or when the real-time hardware controllers signal events such as successful creation of entanglement with a neighboring node.

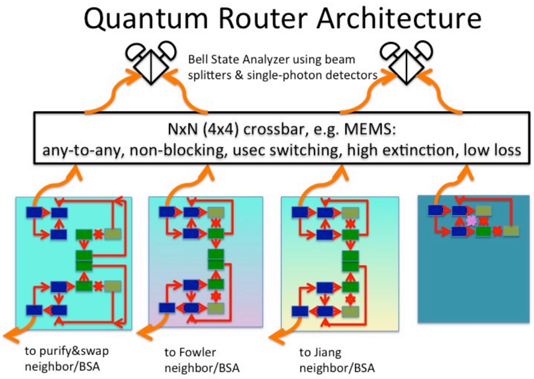


図 3 Proposed quantum router hardware architecture

4. Created artificial topologies for use in large-scale quantum Internet simulation by extracting subsets of the nodes in classical Internet autonomous systems. An example of one of the networks is shown below, created by algorithmically taking a subset of the nodes measured on an Internet Autonomous System.

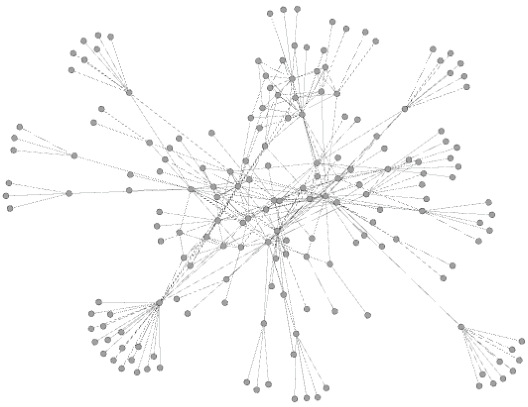


図 4 A quantum network topology derived from an Internet autonomous system

5. Quantum repeater networks depend on deployable hardware, but long-distance overland deployments will be expensive and time-consuming, and undersea deployments of planned hardware types will be difficult due to power, packaging and maintenance requirements. However, we have realized that networks can be implemented by distributing entanglement using long-lived Bell pairs protected using error correction. We term this approach *quantum sneakernet*, in analogy to the classical sneakernet approach of transporting data on removable storage media, as illustrated in 図 5.

We have simulated this approach to determine resource requirements and performance. Placing large-scale quantum computers in shipping containers and entangling them with stationary computers before carrying them via ship to remote locations allows us to circumvent deployment problems and quickly establish quantum networks between any two locations, and will provide tremendous bandwidth (in Bell pairs per second) compared to slower optical methods of creating entanglement over moderate to large distances.

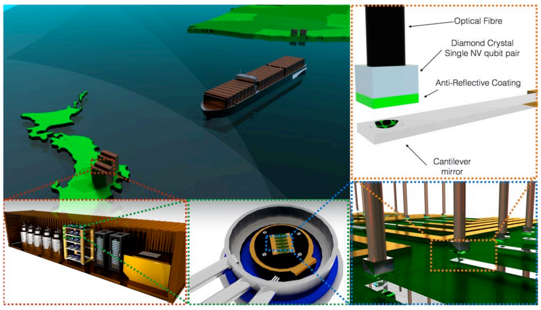


図 5 The Quantum Sneakernet concept

Note that, although the latency of container ships can be measured in weeks, this is an "offline" process, done before the entangled states are required for applications. The applications running at end nodes will operate with millisecond latencies, as in standard networks.

In our opinion, this approach is very likely to be used in the first intercontinental entanglement experiments.

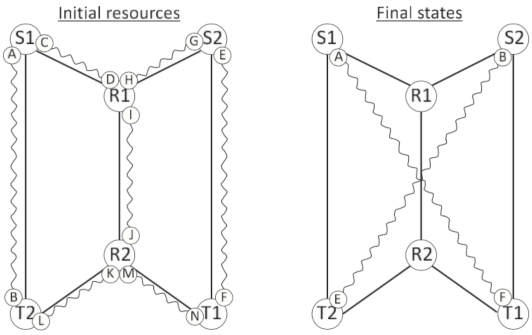


図 6 Quantum network coding on a butterfly network

6. Network coding is a well-known technique for improving the utilization of limited classical network bandwidth by introducing computation at intermediate

nodes in the network. Equivalent techniques for quantum networks have been investigated at the conceptual level, but only using pure states (those with perfect fidelity).

We simulated quantum network coding on a butterfly network for quantum repeaters using Bell pairs with fidelity F < 1.0, as a possible means of using a Quantum Internet efficiently, as shown in 図 6.

We simulated two separate regimes: a range of initial Bell pair fidelities assuming perfect local gates, and two different values of Bell pair fidelity (F=0.95, 0.98) with a range of different values for local gates. The results of the latter simulations are shown in 図 7. We compare to entanglement swapping over a path length of 3. For both F=0.95 and F=0.98 initial Bell pairs, we see that the allowable local gate infidelity for network coding is about half the allowable level for gate-based entanglement swapping.

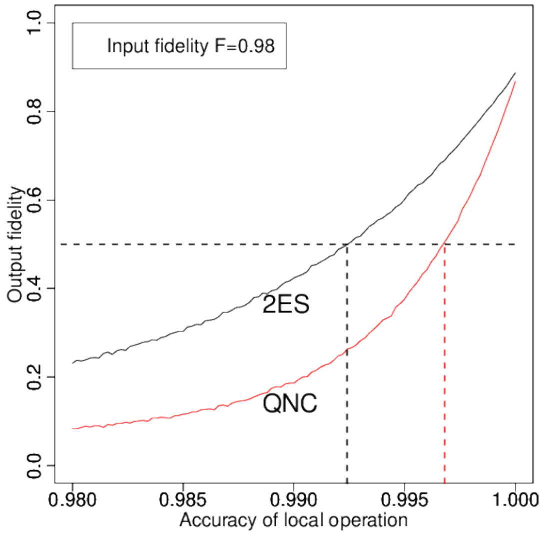


図 7 Output fidelity of QNC vs. direct entanglement swapping over a path of length 3.

7. Finally, it is impossible to design a complete information system without an understanding of how it will be used. In particular, we have begun looking for applications that can be demonstrated in the near term, as quantum repeater hardware begins to appear in the laboratory. We analyzed the demands of quantum key distribution for different deployment scenarios, and studied other applications of distributed entanglement [6]. We created rough designs for circuits for executing Ben-Or and Hassidim's Quantum Byzantine Agreement (QBA), as an application to be run on top of a Quantum Internet.

To fully demonstrate the algorithm, a minimum of five nodes must participate. Our preliminary analysis suggests that 135 Bell pairs must be created and consumed between each pair of nodes for one round of QBA. At current experimentally demonstrated Bell pair production rates, one round will take nearly twenty seconds, therefore requiring a twenty-second memory lifetime. Moreover, as approximately 100,000 gate operations are required to fully execute the algorithm (including identity gates as qubits wait), a local gate error rate of less than 10^-5 may be required.

8. In addition to direct research, we conducted outreach, education, and community service. The book *Quantum Networking* [6] both contains new research results and serves as an educational bridge between the classical networking community and the quantum information community. We also participated in the organization of and attended the first Workshop for Quantum Repeaters and Networks (WQRN), held in May 2015 in Asilomar, California.

<引用文献>

[1] Shota Nagayama, Byung-Soo Choi, Simon Devitt, Shigeya Suzuki, Rodney Van Meter, "Interoperability in Quantum Repeater Networks," *Phys. Rev. A* 93, 042338 (2016), doi: 10.1103/PhysRevA.93.042338.

[2] W. Dür, H.-J. Briegel, "Quantum repeaters based on entanglement purification," *Phys. Rev. A* 59, 169-181, 1999.

[3] L. Jiang, J.M. Taylor, K. Nemoto, W.J. Munro, R. Van Meter, M.D. Lukin, "Quantum repeater with encoding," *Phys. Rev. A* 79, 032325, 2009.

[4] A. G. Fowler, D. S. Wang, C. D. Hill, T.D. Ladd, R. Van Meter, L.C.L. Hollenberg, "Surface code quantum communication," *Phys. Rev. Lett.* 104, 180503, 2010.

[5] R. Van Meter, C. Horsman, J. Touch, "Recursive quantum repeater networks," *Progress in Informatics* 8, 65-79, 2011.

[6] R. Van Meter, *Quantum Networking*, Wiley-iSTE, 2014.

[7] S. J. Devitt, A.D. Greentree, A.M. Stephens, R. Van Meter, "High-speed quantum networking by ship," pre-print arXiv:1410.3224, Oct. 2014 (査読中).

[8] Takahiko Satoh, Kaori Ishizaki, Shota

Nagayama, Rodney Van Meter, "Analysis of Quantum Network Coding for Realistic Repeater Networks," *Phys. Rev. A* 93, 32302 (2016), doi: 10.1103/PhysRevA.93.32302.

５．主な発表論文等

（研究代表者、研究分担者及び連携研究者には下線）

〔雑誌論文〕（計　3件）

1. Shota Nagayama, Byung-Soo Choi, Simon Devitt, Shigeya Suzuki, Rodney Van Meter, "Interoperability in Quantum Repeater Networks," *Phys. Rev. A* 93, 042338 (2016), doi: 10.1103/PhysRevA.93.042338.（査読有り）
2. Takahiko Satoh, Kaori Ishizaki, Shota Nagayama, Rodney Van Meter, "Analysis of Quantum Network Coding for Realistic Repeater Networks," *Phys. Rev. A* 93, 32302 (2016), doi: 10.1103/PhysRevA.93.32302.（査読有り）
3. Alexandru Paler, Ilia Polan, Kae Nemoto, Simon Devitt, "A Regular Representation of Quantum Circuits," *Lecture Notes in Computer Science* 9138, 139-154, 2015, doi: 10.1007/978-3-319-20860-2_9.（査読有り）

〔学会発表〕（計14件）

1. Rodney Van Meter, "量子計算機の可能性と実現手法 Potentialities and Limitations of Quantum Computing Machines," 情報処理学会全国大会、慶應義塾大学（横浜）2016年３月１２日.
2. Rodney Van Meter, "Applications of Quantum Repeater Networks," Asian Internet Engineering Conference, Bangkok, Thailand, 2015年11月18日.
3. Rodney Van Meter, "Distributed Management of Density Matrices," Asian Quantum Information Science Conference, Seoul, Korea, 2015年8月24日～8月30日.
4. Mohammed Amin Taherkhani, Rodney Van Meter, "Performance Analysis of Byzantine Agreement on Quantum Repeater Networks," Asian Quantum Information Science Conference, Seoul, Korea, 2015年8月24日～8月30日.
5. Shigeya Suzuki, Rodney Van Meter, "Classification of Quantum Repeater Attacks," Workshop for Quantum Repeaters and Networks, Pacific Grove, USA, 2015年5月15日～17日.
6. Takahiko Satoh, Rodney Van Meter, "Analysis of Quantum Network Coding for Realistic Repeater Networks," Workshop for Quantum Repeaters and Networks, Pacific Grove, USA, 2015年5月15日～17日.
7. Shota Nagayama, Rodney Van Meter, "Heterogeneous Entanglement Swapping," Workshop for Quantum Repeaters and Networks, Pacific Grove, USA, 2015年5月15日～17日.
8. Rodney Van Meter, Shota Nagayama, Takahiko Satoh, Shigeya Suzuki, "Quantum Internetworking," Workshop for Quantum Repeaters and Networks, Pacific Grove, USA, 2015年5月15日～17日.
9. Alexandru Paler, Simon Devitt, "An introduction to Fault-Tolerant Computing," 52nd Annual Design Automation Conference, San Francisco, USA, 2015年6月7日～6月10日.
10. Rodney Van Meter, "Distributed Density Matrix Management," 17th Annual SQuInT Workshop, Berkeley, USA, 2015年2月20日.
11. Rodney Van Meter, "A Blueprint for Building a Quantum Computer," TTI/Vanguard [NEXT], San Francisco, USA, 2014年12月5日.
12. Rodney Van Meter, "Architectures for Quantum Computers," Spin Qubits 2, Konstanz, Germany, 2014年8月22日.
13. Rodney Van Meter, "Is Valley Fold Timing Optimal for Chains of Quantum Repeaters?" Japan-France Laboratory for Informatics, Quantum Information Workshop, Tokyo, Japan, 2014年3月4日.
14. Rodney Van Meter, "Networks of Networks of Quantum Repeaters," IEEE Comnetsat 2013 (keynote speech), Yogyakarta, Indonesia, 2013年１２月３日.

〔図書〕（計　1件）

Rodney Van Meter, *Quantum Networking*, Wiley-iSTE, 2014, 368 pages, ISBN 978-1-84821-537-5

〔産業財産権〕

○出願状況（計　0件）
○取得状況（計　0件）

〔その他〕

ホームページ等
http://aqua.sfc.wide.ad.jp/

６．研究組織

(1)研究代表者

Ｖａｎ・Ｍｅｔｅｒ　Ｒｏｄｎｅｙ
（VAN METER, Rodney）

慶應義塾大学・環境情報学部・准教授
研究者番号：９０４５８９７７

(2)研究分担者

楠本　博之（KUSUMOTO, Hiroyuki）

慶應義塾大学・環境情報学部・准教授
研究者番号：２０２２５１４７